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Development of High Power CARM Oscillators

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The Cyclotron Auto-Resonance Maser (CARM) is under investigation at the U.S. Naval Research Laboratory as an efficient source of high power millimeter-wave and submillimeter-wave radiation for applications such as plasma heating, advanced rf accelerators, and space-based radars. A short-pulse 100 GHz CARM oscillator experiment based on a 600 kV, 200 Amp. 50 nsec electron beam is under way. The mode selective, high-Q waveguide cavity with rippled-wall Bragg reflectors is designed to operate in the TE_{61} mode. A novel cold cathode diode is used to produce a high quality ($\Delta v_z/v_z \leq 3\%$) annular beam with a momentum pitch ratio of 0.6. The cathode features nonemitting focussing electrodes and an annular velvet emitter. The main objective of the experiment is to demonstrate high efficiency $\gtrsim 20\%$ at a power of ap-

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19. ABSTRACTS (Continued)

proximately 20 MW. In addition, a long pulse 250 GHz CARM oscillator experiment based on a 500 kV, 100 Amp, 1 μsec MIG-type thermionic cathode electron gun is planned. The design of these experiments and the optimization of CARM oscillator efficiency are discussed.

CONTENTS

DEVELOPMENT OF HIGH POWER CARM OSCILLATORS

1 Introduction

There is now a considerable research effort to develop high power, high frequency (millimeter wave to infrared) sources based on high voltage electron beams. These devices, the best known of which is the Free Electron Laser (FEL), are inherently high power and produce high frequencies by a doppler-shift effect which scales as the square of the relativistic mass ratio γ. The U.S. Naval Research Laboratory (NRL) has recently initiated an experimental program on a related device called the Cyclotron Auto-Resonance Maser (CARM) [1]. The frequency of this device is doppler-upshifted by $\sim \gamma^2$ from the relativistic cyclotron frequency (that is, upshifted by $\sim \gamma$ from the nonrelativistic cyclotron frequency). The efficiency potential of the CARM is similar to the gyrotron — of order 20–40% — but higher beam quality is required. Compared to gyrotrons, CARM's can have larger cavity structures for a given wavelength and have lower beam pitch angle. These properties simplify beam formation and reduce self-field effects as well as reducing cavity ohmic losses.

Because the interaction occurs with a forward propagating wave, electrons lose axial momentum—and axial velocity—during the interaction, and this leads high efficiency potential due to an "auto-resonance" effect. That is, the interaction resonance condition:

$$\omega = k_\| v_\| + \Omega_{nr}/\gamma \tag{1}$$

—where ω is the wave frequency, $k_\|$ and $v_\|$ are radiation wavenumber and electron beam velocity components in the beam drift direction, and Ω_{nr} is the nonrelativistic cyclotron frequency — is relatively insensitive to changes in beam energy. This is because the change in the relativistic cyclotron frequency $\Omega = \Omega_{nr}/\gamma$ during the interaction is compensated by a change in the the doppler shift $k_\| v_\|$. This effect reduces the detuning of the resonance condition during beam-wave energy exchange. A combination of high doppler upshift of the frequency and high efficiency occurs when $\beta_{\perp 0} = 1/\gamma_0$ provided that

$$1 - \beta_{ph}^{-2} \le \gamma_0^{-2} \tag{2}$$

where $\beta_\perp = v_\perp/c$ and $\beta_{ph} = v_{ph}/c = \omega/(k_\| c)$. The autoresonance effect leads to high efficiencies without the need for efficiency enhancement schemes based on tapering the

interaction parameters.

A 0.5 MV CARM has the potential for efficient, multi-MW operation at wavelengths of 1.1 mm (280 GHz) with a 63 kG superconducting magnet or 560 GHz with a 125 kG magnet. With a 1 MV beam or operation at harmonics there is a potential for THz frequencies. This potential makes the CARM an attractive candidate for development as a source for the Compact Ignition Tokamak (CIT).

The NRL development effort has chosen to conduct its first experiments on CARM oscillator configurations for several reasons. The CARM circuit generally involves a highly overmoded waveguide structure with the attendant probability of mode competition. Compared to the amplifier, the oscillator configuration appears to offer more alternatives for mode control. Waveguide cavities with rippled-wall Bragg reflectors can be highly selective with respect to frequency and axial mode index. On the other hand quasi-optical cavities have excellent transverse mode selectivity transverse mode selectivity. Because the radiation traverses an oscillator cavity many times instead of once as in an amplifier, the interaction length can be relatively short and this helps prevent the build-up of spurious oscillations which are a major issue for amplifiers, particularly at high frequencies. The short interaction length also helps reduce the sensitivity to beam velocity spread. Additionally, a free-running oscillator does not require a source of input power, an expensive and scarce commodity at submillimeter wavelengths. The amplifier also requires an overmoded but highly mode selective and nonbeam-intercepting input coupler, a difficult engineering problem. The efficiency potential of CARM oscillators and amplifiers appears to be similar, of order 20–40%. The circulating power in a high Q oscillator is generally much greater than the output power. This leads to somewhat greater ohmic losses for a given output power for the oscillator compared to the amplifier; however, oscillators can be designed for megawatt CW powers.

NRL currently has an ongoing short pulse $\sim$ 50 nsec, 100 GHz CARM oscillator experiment based on a 600 kV, 200 Amp electron beam produced by a pulseline accelerator. The objectives of the experiment are to investigate CARM physics and to demonstrate the high efficiency potential of the CARM oscillator at multimegawatt power levels. A 200-300 GHz

CARM oscillator based on a 0.5 MV thermionic cathode electron gun is currently in the design and planning stage. The device would have a pulse length of 1 microsecond and be rep-rated. The goal of the "long pulse" experiment would be to achieve output powers of about 10 MW and efficiencies in the 20-40% range.

2 CARM Efficiency Optimization

Consider the interaction of the electron beam with the TE mode of a vacuum waveguide. The transverse electric field is the form:

$$\vec{E}_\perp(\vec{r}, t) = \Re\left\{ E_0 \vec{z} \times \vec{\nabla}_\perp \psi(\vec{r}) e^{-i\omega t} \right\} \tag{3}$$

where E_0 is the field amplitude, ω is the wave angular frequency, and ψ is the mode scalar function. For a TE_{mn} circular waveguide mode , the scalar function is given by:

$$\psi(\vec{r}) = C_{mn} J_m(k_{mn} r) e^{im\theta} \tag{4}$$

where J_m is a Bessel function of the first kind, m is the azimuthal index, n is the radial index, and x_{mn} is the nth zero of J_m. The mode normalization coefficient C_{mn} is given by:

$$C_{mn} = \left\{ \sqrt{\pi\left(x_{mn}^2 - m^2\right)} J_m(x_{mn}) \right\}^{-1} \tag{5}$$

As shown by Fliflet [2], application of single particle theory to the CARM interaction for the sth harmonic leads to the following normalized equations of motion:

$$\frac{du}{d\zeta} = (1 - u)^{s/2} \Re\left\{ F_s e^{-i\Theta} \right\} / (1 - bu) \tag{6}$$

$$\frac{d\Theta}{d\zeta} = \left[\Delta - u + \frac{s}{2}(1 - u)^{s/2 - 1} \Re\left\{ iF_s e^{-i\Theta} \right\} \right] / (1 - bu) \tag{7}$$

where u is the normalized electron energy:

$$u = \frac{2}{\beta_{\perp 0}^2} \left(1 - \beta_{\|0}/\beta_{ph} \right) \left(1 - \gamma/\gamma_0 \right), \tag{8}$$

Θ is a slowly varying phase, F_s is the normalized wave amplitude function, which for the fundamental harmonic interaction is given by:

$$F_1 = \frac{2e}{\gamma_0 m_0 c^2} \frac{\left(1 - \beta_{\|0}/\beta_{ph} \right)^2}{\beta_{\perp 0}^3 \sqrt{1 - \beta_{ph}^{-2}}} C_{mn} J_{m-1}(k_{mn} r_b) E_0, \tag{9}$$

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ζ is the normalized axial coordinate:

$$\zeta = \frac{\beta_{\perp 0}^2}{2\beta_{\parallel 0}} \frac{1 - \beta_{ph}^{-2}}{1 - \beta_{\parallel 0}/\beta_{ph}} \left(\omega z/c\right),$$ (10)

Δ is the resonance detuning parameter:

$$\Delta = \frac{2 \left(1 - \beta_{\parallel 0}/\beta_{ph}\right)}{\beta_{\perp 0}^2 \left(1 - \beta_{ph}^{-2}\right)} \left(1 - \beta_{\parallel 0}/\beta_{ph} - s\Omega/\omega\right)$$ (11)

and b is the electron recoil parameter:

$$b = \frac{\beta_{\perp 0}^2}{2\beta_{\parallel 0}\beta_{ph} \left(1 - \beta_{\parallel 0}/\beta_{ph}\right)}$$ (12)

In Equation (9), e is the magnitude of the electron charge, and m_0 is the electron mass. The electron axial and transverse momenta are given by:

$$p_{\parallel} = \gamma_0 m_e c \beta_{\parallel 0} \left(1 - bu\right)$$ (13)

$$p_{\perp} = \gamma_0 m_e c \beta_{\perp 0} \sqrt{1 - u}$$ (14)

The electron recoil parameter b characterizes how the axial momentum varies with beam energy; as shown in Eq.(14), the larger b is, the more rapidly the axial momentum decreases with decrease in γ. The CARM interaction is characterized by $b \sim 0.3$–0.6, the gyrotron regime is obtained by setting $b = 0$.

The electronic efficiency can be written in the form: $\eta = \eta_{sp}\hat{\eta}$ where η_{sp} is the is the single particle efficiency given by:

$$\eta_{sp} = \frac{\beta_{\perp 0}^2}{2 \left(1 - \beta_{\parallel 0}/\beta_{ph}\right) \left(1 - \gamma_0^{-1}\right)}$$ (15)

and $\hat{\eta}$ is the normalized efficiency given by:

$$\hat{\eta} = \int_0^{2\pi} u \left(\mu, \Theta_0\right) d\Theta_0$$ (16)

where μ denotes the normalized interaction length and Θ_0 is the initial value of the slowly varying phase parameter. For a given harmonic, recoil parameter, and axial profile for the wave field, the normalized efficiency for optimized Δ can be presented on an $F - \mu$ plot

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similar to the plot used to characterize the gyrotron [3]. The parameter F defined in this paper divided by two is equal to the amplitude parameter F defined by Danly *et al* [3] in the limit: $b \to 0, \beta_{ph} \to \infty$. A plot of optimized constant normalized efficiency contours as a function of F and μ is shown for the case of $b = 0.4$ and constant wave field amplitude in Figure 1. The corresponding iso-Δ values are shown in Figure 2. Figures 1 and 2 show that for a constant field profile, the maximum normalized efficiency is $\approx 36\%$ and the optimum parameters are $F = 0.2$, $\mu = 8$, and $\Delta = 0.6$. It is of interest to note that in the gyrotron limit ($b = 0$), the optimum normalized efficiency is 42%. In the case of the gyrotron the normalized efficiency can be increased to over 70% by suitably profiling the axial profile of the wave field and it is expected that a similar enhancement for the CARM can be achieved using this technique.

3 Short-Pulse 100 GHz CARM Oscillator

A Proof-of-Principle experiment based on a waveguide cavity with a Bragg reflectors has been set up to investigate the CARM configuration. The device is designed to operate at 100 GHz with a 600 KV, 200 Amp electron beam produced by a *pulseline accelerator* with a pulselength of $\sim$ 50 nsec. The choice of beam and cavity parameters is based on the theory outlined in Section 2. This theory, which assumes a cold beam, predicts an efficiency of 20% at a power of 24 MW. A schematic of the device configuration is shown in Figure 3. The annular electron beam propagates near the wall of the Bragg reflector waveguide cavity which has been optimized for the TE_{61} circular waveguide mode.

The ability to produce a high quality beam is considered critical to the success of this experiment, a major objective of which is to demonstrate high efficiency for the CARM interaction. The beam quality requirement can be estimated by a simple coherence argument. The constraint on axial velocity spread is:

$$\Delta v_{\parallel}/v_{\parallel} < \lambda/(2L) \tag{17}$$

for no spread in beam energy. Equation (17) can readily be expressed as a constraint on pitch angle spread. The constraint on energy spread for a beam with no pitch angle spread

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is

$$\frac{\Delta\gamma}{\gamma} < \frac{(1-\gamma_0^{-2})(\lambda/2L)}{(1+\alpha^2)(\Omega/\omega - \gamma_0^{-2})} \tag{18}$$

where α is the average momentum pitch ratio of the beam. These relationships lead to the curves for axial momentum, pitch angle, and energy spread shown in Figure 4 for a 600 kV CARM with $\beta_\perp = 1/\gamma_0$. These curves show that there is greater sensitivity to pitch angle spread than to energy spread, a feature related to the auto-resonant character of the interaction. Note that the denominator of Eq.(18) can be small when $\gamma \gg 1$ since in this case for the CARM $\omega/\Omega \approx \gamma^2$. The required tolerances are considered achievable except for group velocities very close to the speed of light. To minimize sensitivity to beam velocity spread, a group velocity of $0.86c$ was chosen for the 100 GHz short pulse experiment.

The cold cathode diode is expected to produce a highly laminar space-charge-limited-flow beam via the use of nonemitting focussing electrodes. The cathode is anodized aluminum with a velvet or graphite emitting surface. The diode is expected to produce a high quality beam with only a few percent spread in axial momentum. This diode is based on a theory of relativistic laminar flow diodes recently developed at NRL by Finn, Fliflet and Manheimer [4]. The transverse momentum required for the CARM interaction is provided by a nonadiabatic dip in the applied magnetic field followed by adiabatic compression of the magnetic field [5]. Simulations of the beam formation system carried out using the Herrmannsfeldt Electron Trajectory Code [6] indicate that an axial velocity spread of about 3% in the interaction region should be obtainable with this system.

An important feature of the Bragg reflector cavity is that it is has a high Q factor for only a limited range of axial wavenumbers. Our design studies for the 100 GHz CARM experiment indicate that this type of cavity can be highly selective with respect to both transverse and longitudinal mode indices [7,8]. Other advantages of this type of resonator include compactness which facilitates beam transport and magnet design, and the possibility of profiling the cavity fields for efficiency enhancement similarly to what is done for gyrotrons. A Bragg cavity and associated radiation profile are shown in Figure 5. The depth of the Bragg ripples is considerably exaggerated. The TE_{61} whispering gallery mode with $Q \approx 1500$ was chosen as the operating mode. This type of mode couples well to both the

electron beam and to the Bragg reflectors. Other whispering gallery modes with radial index $n = 1$ represent the principal CARM-type competing modes. The frequency separation of 3 GHz should prevent competition between these modes while allowing step-tunability. Another important feature of this cavity is that reflector bandwidth was chosen sufficienctly narrow that there is only a single axial mode per transverse mode. The CARM mode Q factor must be chosen high enough to prevent competition from low frequency (gyrotron) modes.

4 Long-Pulse CARM Oscillator

The present 600 kV, 100 GHz CARM oscillator project is expected to provide important data on the potential of the CARM as an efficient high power source. However, a thermionic cathode experiment is essential for complete investigation of CARM issues. A preliminary design has been obtained at for a 500 kV, 250 GHz thermionic cathode device. A 55 kG magnetic field —produced by a superconducting magnet—is required for operation with $\beta_\perp = 1/\gamma$. A TE_{14} mode has been chosen based on output power, e-beam size, and wall heating considerations. High power operation in a waveguide cavity at wavelengths ≤ 1 mm requires group velocities close to the speed of light with attendant sensitivity to beam quality. This results from the need for cavity dimensions large compared to the wavelength and the need to control ohmic heating. A group velocity of 0.97c was chosen for the preliminary design. An output power of 10 MW is obtained for 92% output reflectivity and the wall loading is about 3 kW/cm^2 for the optimum efficiency wave amplitude. The peak electric fields at the wall are less than 50 KV/cm for the TE_{14} mode. Operation at 10% duty factor would result in an average power of 1 MW and an average wall loading of 0.3 kW/cm^2. The computed cold beam efficiency is $\sim 20\%$ and the required beam current is 100 Amps. The cavity radius is 9.3 mm and the electron beam radius for a beam placed on the third E-field peak — this avoids coupling to whispering gallery modes which have high ohmic losses — is 5.6 mm. An annular electron beam is generated by a temperature-limited MIG type 500 kV electron gun. The cathode emission current density is ~ 10 A/cm^2 at a current of 100 Amps, a cathode loading compatible with high duty factor operation.

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The gun perveance is 0.28 μperv. For comparison, the gun for the SLAC klystron has a perveance of 2 μperv; thus space-charge defocussing effects should be controllable. Very low pitch angle spread (a critical CARM requirement) should be obtainable with this type of gun. The design goal is an axial momentum spread of a few percent. This experiment should provide highly a relevant technology base for a burst mode 280 GHz source for CIT or Alcator C-Mod.

A preliminary electrode design has been obtained for a 500 kV, 100 Amp, 1 μsec pulse length MIG-type electron gun. Based on calculations using the Herrmannsfeldt Electron Trajectory Code, the electrodes produce a highly laminar, temperature-limited, annular electron beam with a final momentum pitch ratio $\alpha \sim 0.5$ and very low axial velocity spread, $\Delta v_{\|}/v_{\|} \sim 1\%$. A schematic of the gun is shown in Figure 6.

Volume TE modes such as TE_{0n} or TE_{1n} type modes have much lower wall losses due to ohmic heating and lower peak rf fields at the wall than whispering gallery ($TE_{m1}, m \gg 1$) modes and are therefore of interest for high duty factor applications. However, special cavity designs are required to select these modes. Possible approaches include the use of axial slots to select TE_{1n} modes or suppression of axial currents (wire-walled waveguide) for TE_{0n} modes. Quasi-optical cavity configurations will also be investigated. The attractiveness of such cavities increases with increase in the radiation frequency since for high power it becomes necessary to increase cavity size relative to the wavelength. Open mirror quasi-optical cavities also allow the wave phase velocity to be controlled independently of the transverse mode or transverse dimensions of the cavity. As discussed by Sprangle et al [9], this control is obtained by varying the angle between the radiation and beam propagation directions. The phase velocity can also be chosen to minimize the effect of beam energy spread. Quasi-optical cavities have excellent transverse mode selectivity and should not support low frequency (gyrotron) modes.

5 Acknowledgment

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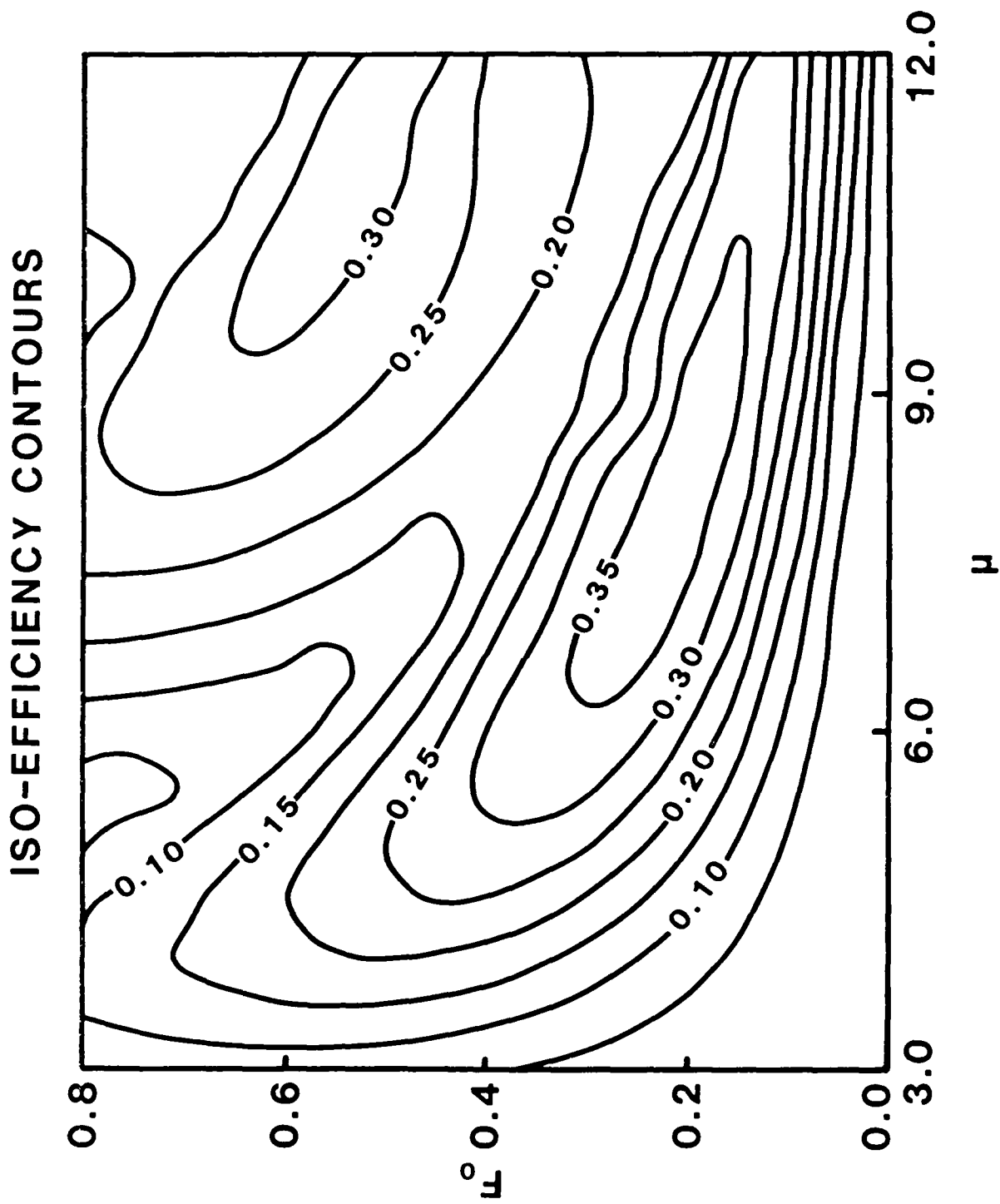
Figure 1. $F - \mu$ plot of optimum normalized efficiency for a constant amplitude wave and $b = 0.4$.
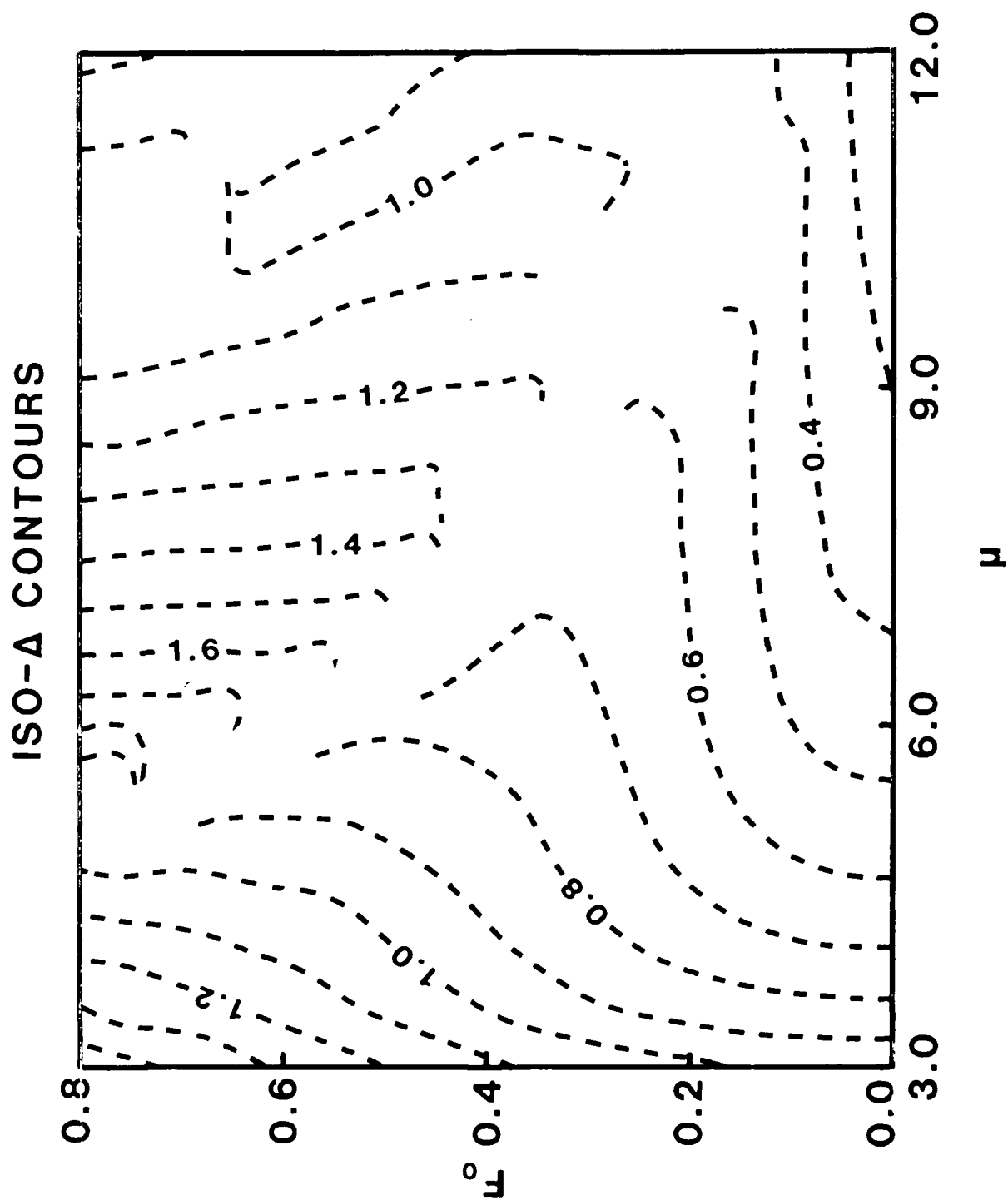
Figure 2. $F - \mu$ plot of Δ corresponding to optimum efficiency for a constant amplitude wave and $b = 0.4$.
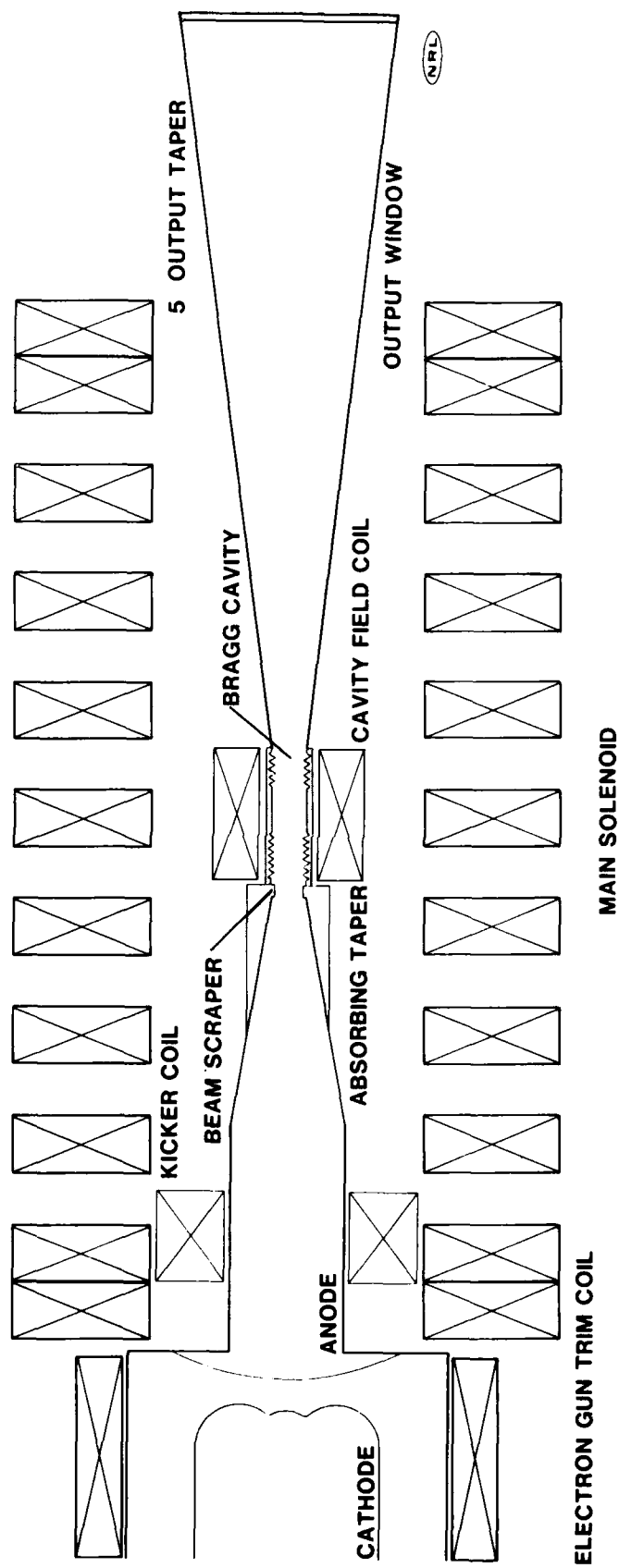
Figure 3. Schematic of 100 GHz short-pulse CARM Oscillator experiment.
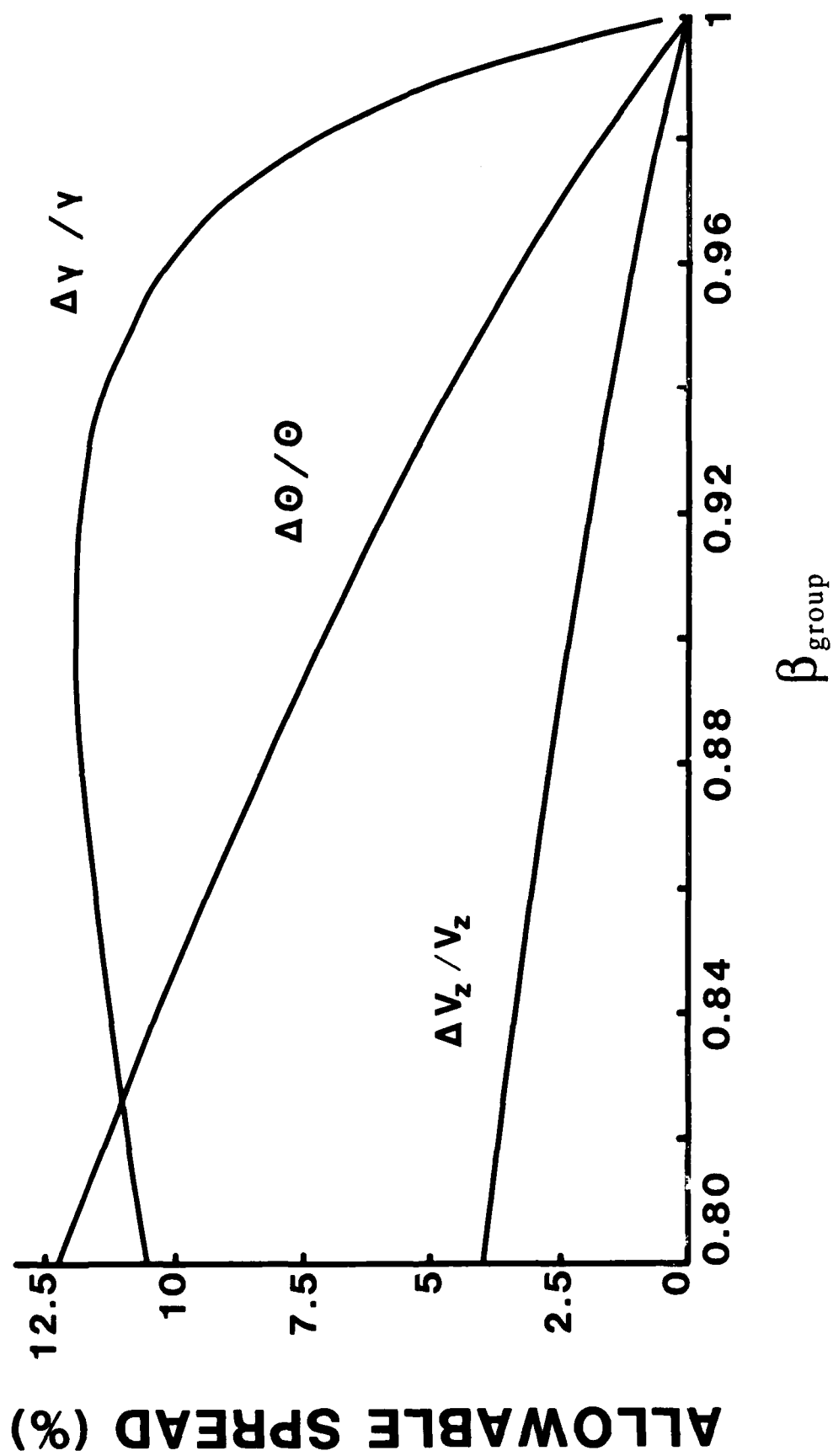
Figure 4. Electron beam quality requirements for a 600 kV CARM oscillator with $\beta_\perp = 1/\gamma_0$.

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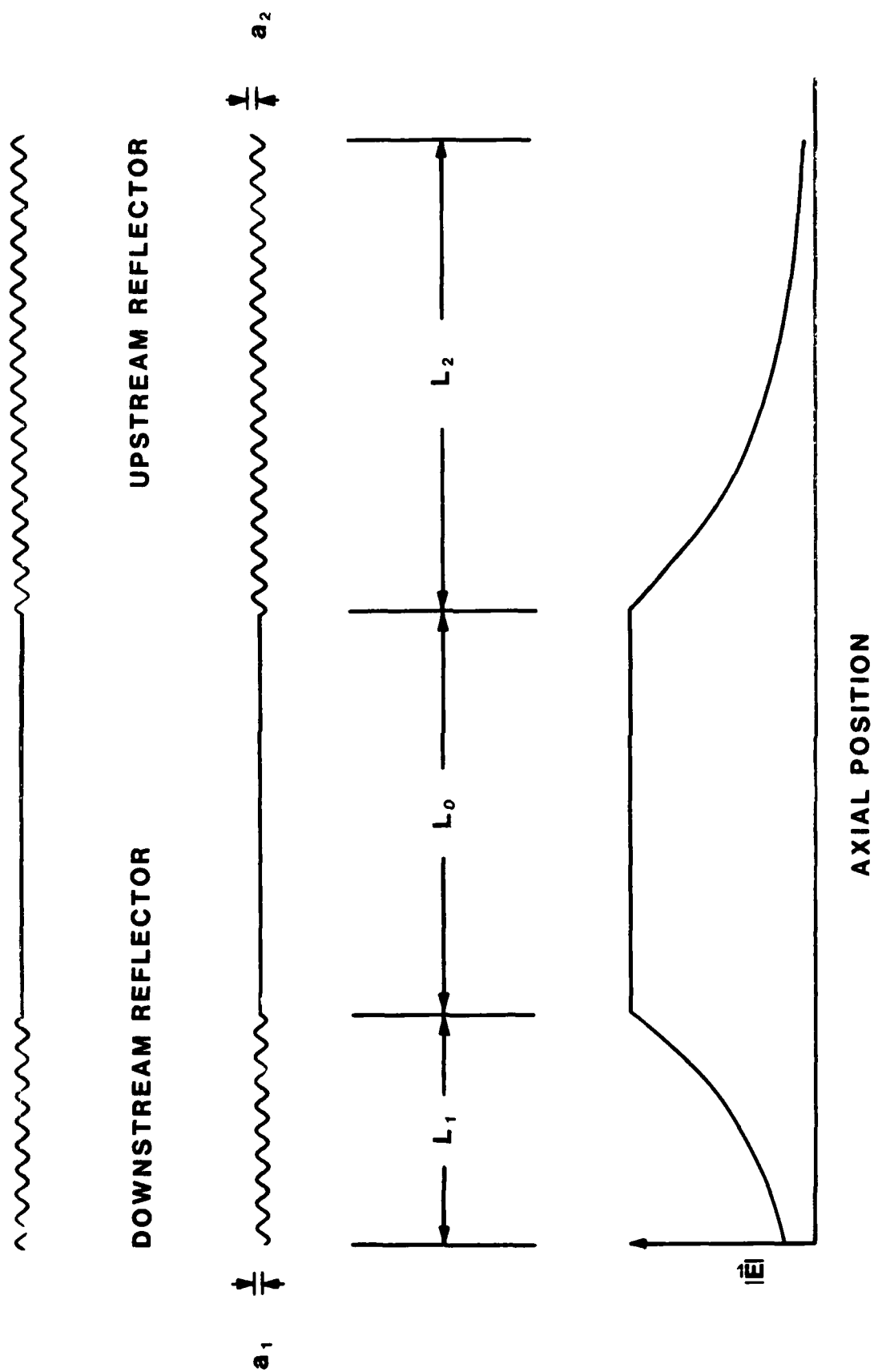
Figure 5. CARM waveguide cavity with Bragg reflectors and associated radiation profile.

DOWNSTREAM REFLECTOR

UPSTREAM REFLECTOR

AXIAL POSITION
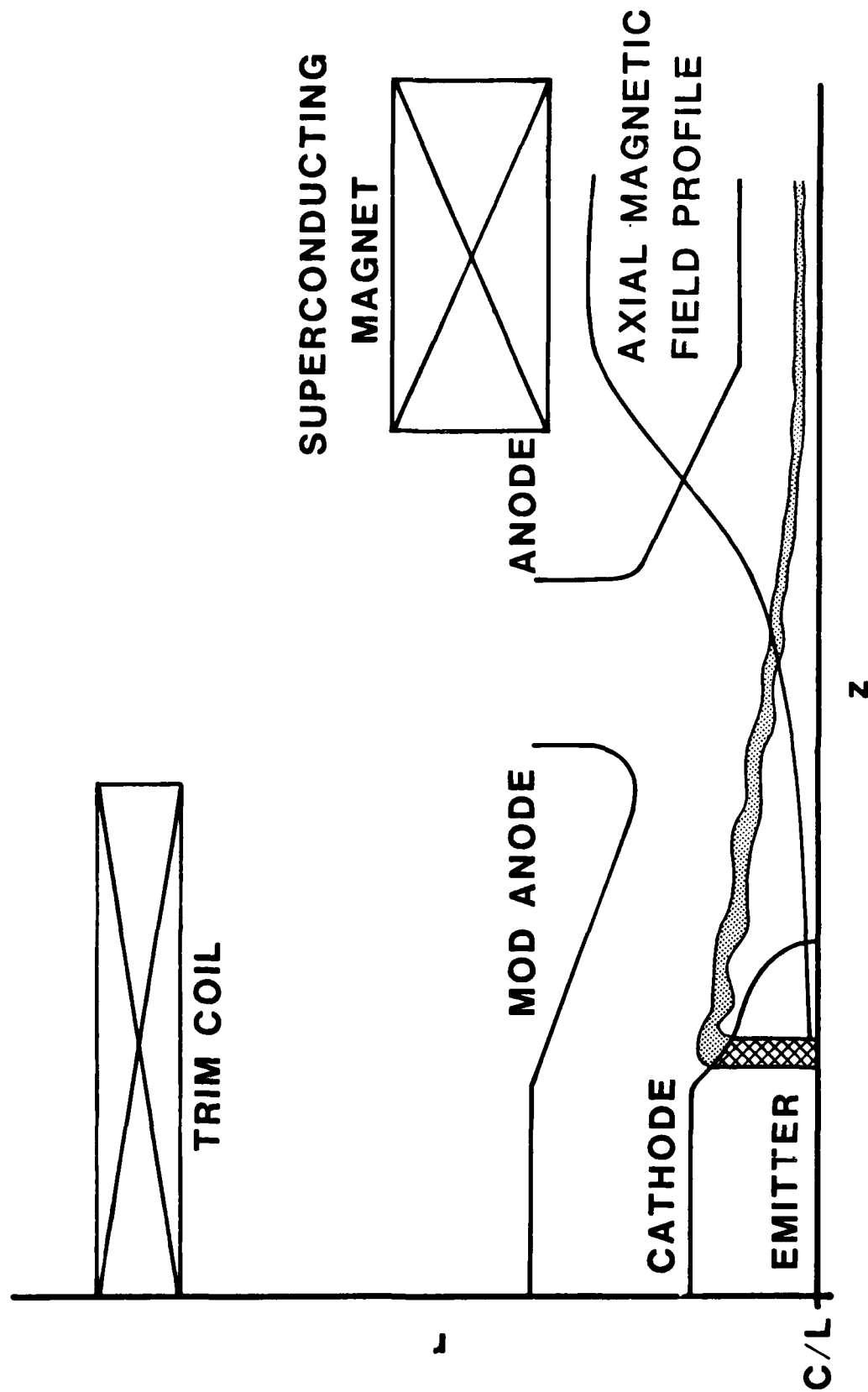
Figure 6. Schematic of a 500 kV, temperature-limited cathode, MIG-type electron gun for a 250 GHz CARM oscillator.

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